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# The use of X-ray densitometry to evaluate the wood density profile of *Tectona grandis* trees growing in fast-growth plantations

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ABSTRACT

*Tectona grandis* (teak) is an important commercial tree species that is widely used in tropical dendrochronology due to the formation of climate-sensitive annual growth rings. However, young trees growing in plantation conditions exhibit poor ring visibility during the first years of growth, limiting the dendrochronology application. In the present study, we use x-ray densitometry to determine the wood density profile between and within annual rings and at the sapwood-heartwood boundary in trees from fast-growth plantations. The resulting wood density profiles (WDP) can be categorized as uniform, stable growth, unstable growth, and false. The annual ring boundaries were indistinct in trees less than 8 years old. In mature trees, the annual ring boundaries are more defined. In relation to the sapwood-heartwood boundary, the WDP showed a decrease in the wood density; however, this decrease is influenced by the annual ring boundary when the two boundaries coincide. The identification of annual rings in trees growing in fast-growth plantations should be combined with X-ray densitometry and visual identification if wood density data are necessary for deriving other analysis, as climate change, from annual ring.

## 1. Introduction

Teak (*Tectona grandis* L.f) is one of the most mportant commercial tropical species worldwide (FAO, 2013). It is native to Southeast Asia, specifically India, Laos, Myanmar, and Thailand (Pandey and Brown, 2001), but commercial teak plantations now exist in Latin America, Asia, Africa, and Oceania (Ladrach, 2009; Kollert and Cherubini, 2012). As a result, commercial teak is often found growing in ecological conditions that differ considerably from its natural habitat in Asia, particularly in relation to geography (elevation and soil fertility) and precipitation (De Camino et al., 2002; Kollert and Cherubini, 2012). Thus, annual rings may exhibit different patterns of variation, perhaps even lacking well-defined rings.

To overcome this challenge, wood density profiles (WDP) have been developed to establish density variations with tree age between and within annual rings, and between annual ring and sapwood-heartwood boundaries (Jacquin et al., 2017). The most important technique utilized in WDP is x-ray densitometry (Jacquin et al., 2017), which provides density values in short intervals. WDP are used in dendrochronological studies (Schöngart et al., 2017) to build time series and to compare dating quality and climate relationships in older trees. WDP are especially useful for understanding growth dynamics in trees that don't exhibit clear annual rings and can be used to define management conditions at the plantation (Jacquin et al., 2017).

*T. grandis* exhibits ring-porous to semi-ring porous wood with well-differentiated annual rings due to the pore size and, in some cases, to the formation of an apparently marginal parenchyma band. The annual rings in teak can be distinguished by WDP (Deepak et al., 2010; Nocetti et al., 2011). Nocetti et al. (2011) used X-ray densitometry to generate WDP and they explained the variations in WDP in relation to anatomy across to the annual rings.

In Asia, the study of WDP of teak annual rings by X-ray densitometry demonstrated that annual rings provide valuable information regarding dendroclimatology (Shah et al., 2007; Ram et al., 2008; Deb et al., 2017) because variations in the WDP depend mainly on precipitation and soil humidity (Pumijumnong, 2013). An important utilization of WDP is establishing chronologies in teak trees, which can be used in studies of plantation management or of trees growing in natural forest (D'Arrigo et al., 2008; Buckley et al., 2007). Several studies of WDP in Thailand have demonstrated the relationship between tree growth and environmental factors such as soil humidity, precipitation, and ambient temperature (Palakit et al., 2015; Buajan et al., 2016; Muangsong et al., 2016; Sangram et al., 2016). However, the majority of existing studies are based on trees older than 100 years, so there is a lack of information regarding annual ring formation and WDP of trees from fast-growth plantations.

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The study of the formation, anatomical composition, and WDP of annual rings in tropical species such as *T. grandis* is more complex than similar studies of species from temperate climates because annual rings are not well-defined (Pumijumnong, 2013) due to a lack of uniformity in the anatomical structure due to strong seasonality (Moya and Tomazello, 2007). Rainfall levels, the phenology of the species, and the periodicity of cambial activity influence ring formation in these regions (Worbes, 2010; Brienen et al., 2016). Plantation management activities to improve tree growth at early ages further affect WDP.

Previous studies have focused on century-old trees because they aim to reconstruct climate using tree-rings as proxies (Jacoby and D'Arrigo, 1990; Deb et al., 2017). The lifespans of young trees found on fast-growth plantations are within the instrumental period, so climate can be obtained from instrumental data (Copenheaver and Abrams, 2003). However, the study of WDP in young trees can help to understand growth dynamics, the growth-climate relationship of teak in different climatic regions, or help to predict sawlog production (Jacquin et al., 2017). Interestingly, Moya (2002) showed that WDP studies can be used to examine how growth-climate relationships changed in different regions of Costa Rica over a period of 30 years. Similarly, Jacquin et al. (2017) showed that WDP can provide information about how trees allocate carbon in response to climate.

However, tropical woody species typically exhibit poor ring visibility for the first several years of growth (4–8 years; Worbes, 2002). If the goal is to model tree growth for ecological or forest management applications, poor ring visibility can make it difficult to obtain realistic growth curves for the early stages of growth (Worbes, 2010). In this case, annual ring determined using WDP cannot be established adequately, which can create estimate errors in variables derived from WDP.

Teak has been planted in a variety of climatic and topographic conditions in Costa Rica and elsewhere (Moya and Pérez, 2008; Moya et al., 2014). Therefore, a great variety of WDP are to be expected within a tree, among trees of different ages, between and within annual rings, and between annual rings and the sapwood-heartwood boundary. The objective of the present study is to better understand how WDP vary between and within annual rings and between annual rings and the sapwood-heartwood boundary in trees from fast-growth plantations. We are particularly interested in understanding whether density profiles are homogeneous within plantations but vary between plantations from different regions. If WDP are consistent within plantations, it may be possible to identify the best provenances for high-quality teak wood in Costa Rica and elsewhere. We hypothesize that moisture-sensitive sites are most suited for high-quality wood production.

## 2. Methodology

### 2.1. Study area

Fifty-four fast-growth *Tectona grandis* plantations, with ages varying from 2 to 22 years, were sampled in five regions of Costa Rica (Table 1). The regions were:

(i) North-Pacific, with 1626 mm of precipitation annually, a dry season from April to November, an average annual temperature of 27 °C, and an average relative humidity of 73%;
(ii) Central-Pacific, with 3743 mm of annual precipitation distributed mostly from April to December, an average annual temperature of 27 °C, and an average relative humidity of 84%;
(iii) South-Pacific, the region with the greatest annual precipitation at 4454 mm distributed throughout the entire year but with the most rainfall concentrated in September and October, an average annual temperature of 27 °C, and an average relative humidity of 75%;
(iv) Atlantic, with 3567 mm of precipitation annually and the driest period in September, an average annual temperature of 27 °C, and an average relative humidity of 86%;

**Table 1**
Dasometric parameters and age of the *Tectona grandis* Lf fast growth plantations sampled in different places in Costa Rica.

| Number of plantation | Region | ID | Age (years) | N (n/ ha$^{-1}$) | DBH (cm) | Ht (m) | hc (m) |
|---|---|---|---|---|---|---|---|
| 1 | PN | C3 | 9 | 556 | 25.1 | 19.4 | 8.8 |
| 2 | PN | C49 | 9 | 556 | 25.1 | 19.1 | 8.8 |
| 3 | PN | S1 | 5 | 358 | 18.3 | 17.3 | 5.6 |
| 4 | PN | S4 | 20 | 377 | 26.2 | 23.7 | 10.3 |
| 5 | PN | PN1 | 22 | 207 | 25.0 | 22.3 | 9.3 |
| 6 | PN | QH1 | 19 | 207 | 33.3 | 24.4 | 12.0 |
| 7 | PN | QH2 | 14 | 433 | 24.5 | 21.6 | 10.0 |
| 8 | PN | PB1 | 19 | 180 | 28.1 | 23.8 | 6.0 |
| 9 | PN | PB2 | 5 | 700 | 10.1 | 13 | 6.5 |
| 10 | PN | N1 | 8 | 450 | 19.2 | 14.1 | 4.2 |
| 11 | PN | N2 | 15 | 320 | 26.3 | 18.9 | 5.8 |
| 12 | PN | N3 | 14 | 320 | 23.6 | 19.8 | 6.8 |
| 13 | PN | J1 | 12 | 264 | 24.9 | 24.1 | 11.0 |
| 14 | PN | RB1 | 13 | 377 | 23.9 | 22.4 | 11.6 |
| 15 | PN | RB2 | 17 | 264 | 27.3 | 26.4 | 11.9 |
| 16 | PN | SP1 | 18 | 433 | 24.3 | 20 | 7.3 |
| 17 | PN | CY1 | 10 | 358 | 21.0 | 17.7 | 6.1 |
| 18 | PN | LJ1 | 4 | 791 | 12.2 | 11.3 | 4.4 |
| 19 | PN | TU1 | 5 | 565 | 16.1 | 13.4 | 3.6 |
| 20 | ZN | SJ1 | 9 | 320 | 12.1 | 15.7 | 6.4 |
| 21 | ZN | SJ2 | 7 | 584 | 14.6 | 17.2 | 5.8 |
| 22 | ZN | SC1 | 7 | 753 | 13.9 | 16.3 | 5.5 |
| 23 | ZN | SC2 | 8 | 735 | 13.8 | 16.4 | 4.9 |
| 24 | ZN | PT1 | 2 | 1111 | 9.3 | 8.7 | 3.6 |
| 25 | PC | LA2 | 3 | 640 | 8.29 | 8.99 | 4.3 |
| 26 | PC | LA3 | 13 | 377 | 23.73 | 21.51 | 9.8 |
| 27 | PC | LA4 | 16 | 339 | 21.23 | 22.04 | 11.2 |
| 28 | ZN | PT2 | 9 | 440 | 18.0 | 15.8 | 4.1 |
| 29 | ZN | PT3 | 10 | 410 | 18.7 | 16.5 | 5.2 |
| 30 | ZN | PV1 | 10 | 414 | 21.3 | 18.9 | 5.9 |
| 31 | ZN | PV2 | 9 | 414 | 21.9 | 18.1 | 5.1 |
| 32 | ZN | PV3 | 6 | 1111 | 16.7 | 14.9 | 5.5 |
| 33 | ZN | PV4 | 5 | 1111 | 20.0 | 15.9 | 5.3 |
| 34 | ZN | B1 | 8 | 716 | 15.4 | 15.6 | 5.8 |
| 35 | ZN | B2 | 11 | 358 | 21.9 | 19 | 7.3 |
| 36 | ZN | P1 | 20 | 264 | 23.8 | 16.7 | 7.2 |
| 37 | ZN | SJA2 | 15 | 358 | 23.9 | 17.7 | 8.1 |
| 38 | PC | SQ1 | 12 | 320 | 21.8 | 16.5 | 8.0 |
| 39 | PS | PM1 | 19 | 471 | 16.8 | 16 | 8.1 |
| 40 | PS | SI1 | 16 | 320 | 22.2 | 15.7 | 6.1 |
| 41 | PS | PJ1 | 3 | 791 | 9.3 | 9.4 | 2.0 |
| 42 | PS | ER1 | 13 | 414 | 24.0 | 18.1 | 10.3 |
| 43 | PS | SA1 | 11 | 523 | 24.3 | 19.6 | 8.1 |
| 44 | PS | SA2 | 10 | 644 | 23.2 | 20.0 | 11.4 |
| 45 | PS | SA3 | 9 | 621 | 22.6 | 19.1 | 8.2 |
| 46 | PS | SA4 | 8 | 460 | 23.3 | 20.2 | 9.5 |
| 47 | PC | PA1 | 18 | 226 | 31.5 | 26.9 | 11.9 |
| 48 | PC | PA2 | 19 | 377 | 27.8 | 27.6 | 14.8 |
| 49 | PC | PA3 | 17 | 264 | 30.5 | 29.7 | 16.1 |
| 50 | PC | PR1 | 24 | 226 | 30.3 | 25.7 | 12.4 |
| 51 | PC | PR2 | 17 | 226 | 27.5 | 24.4 | 11.6 |
| 52 | PC | PR3 | 19 | 264 | 28.0 | 21.6 | 9.0 |
| 53 | PC | PR4 | 15 | 556 | 22.3 | 17.7 | 7.6 |
| 54 | PC | LA1 | 18 | 452 | 20.5 | 23.1 | 11.6 |

Legend: ID = Plantation identification; N = stand density DBH = diameter at breast height; Ht = total height; hc = height to crown start; PN = North Pacific. PC = Central Pacific. PS = South Pacific. ZN = northern zone.

(v) Northern, with 1732 mm of precipitation annually and rainfall distribution from May to January, an average annual temperature of 24 °C, and an average relative humidity of 86% (Fig. 1) (IMN (Instituto Meteorológico Nacional de Costa Rica), 2017).

The number of plantation samples varied per region: 16 from the Central-Pacific, 12 from the North-Pacific, 7 from the South-Pacific, 1 from the Atlantic Region, and 18 from the Northern Region (Fig. 1). In the case of the Atlantic Region, the low number of samples is a consequence of the small area planted with *T. grandis*; therefore; a permit to fell more trees in the region was not granted. Three trees were sampled

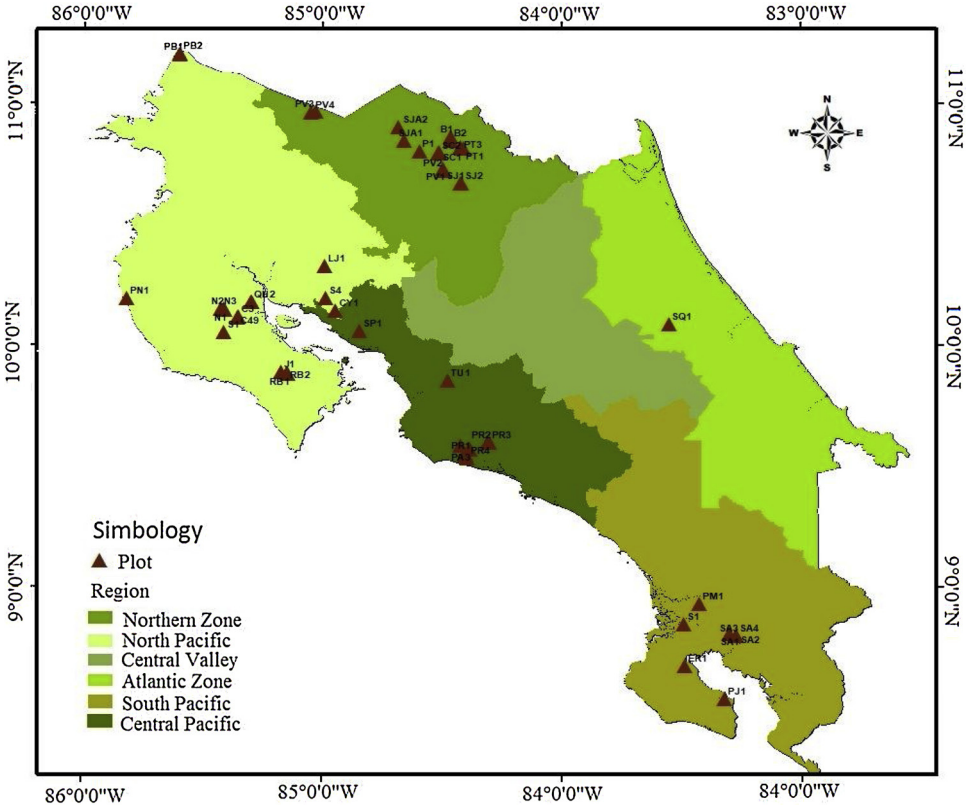


**Fig. 1.** Distribution of *Tectona grandis* sampled plots of different ages in fast-growth plantations in Costa Rica.

in each plantation, for a total of 162 sampled trees (Berrocal et al., 2019).

### 2.2. Plantation and tree sampling

For each sampling plantation, a temporary 13-m radius (531 $m^2$) plot was established. All of the trees inside each plot were measured, as were the following variables (Table 1): total number of trees (N), diameter at breast height (DBH), crown initial height (hc), and total height ($h_t$). After measuring the plot, three trees with straight trunks and no signs of disease were randomly selected. After selecting the trees and recording their DBH, the trees were cut and the $h_t$ was measured. Afterward, 4-cm thick cross-sections were taken every 2.3 m starting from the base of the trees up to a maximum height of 7.1 m.

### 2.3. Sample preparation for densitometry measurements

In each of the cross-sections, a 4-cm wide broad bar was initially cut in the north-south direction (Fig. 2a). A 1-cm wide sample was then cut in the same direction, passing through the tree pith (Fig. 2b). This sample was separated at the pith to obtain a subsample north and a subsample south (Fig. 2b). A 1-cm thick piece was cut from each section (Fig. 2c). These 1 cm × 1 cm sections were glued radially onto a wood support (Fig. 2d). The pieces were then cut with a double circular saw to extract 2-mm thick samples for the X-ray densitometry thickness analysis (Fig. 2e).

### 2.4. X-ray densitometry measurement

The thin teak samples were conditioned at 12% moisture content in a chamber with a temperature of 22 °C and 66% relative humidity. The X-ray densitometry measurement was performed in the transverse direction (Fig. 2e). Each thin sample was placed on the bracket included with the X-ray equipment, an X-ray photograph was taken, and the density profile was determined. Sample exposure was performed using an X-ray scanner from Quintek Measurement Systems Inc. (model QTRS-01X) at 7 kV tension in the tube, and the density readings were carried out for 1 s every 40 µm. The actual density of each thin sample was previously determined by weighing it with a precision scale and measuring its length, height, and thickness to calculate the volume.

### 2.5. Density profile from pith to bark

The density values obtained using X-ray densitometry were plotted in relation to the distance from the pith. The density variation profiles were carefully observed to obtain variation patterns throughout all radial sections (pith to bark). Density patterns and the existence of annual ring boundaries for trees of different ages were then established. Ring boundaries were identified by a peak in the X-ray density profile caused by an increase in the density at the end of the ring.

### 2.6. Annual ring boundary and classification

X-ray photographs were obtained for all thin samples using a Faxitron® LX-60 Cabinet X-ray System (Hewlett Packard, Lincolnshire, IL, USA), leaving 12 cm between the X-ray source and the samples. Samples were exposed for 15 s at 30 kV tension within the tube. To evaluate the annual ring boundary, x–y graphics were created from the X-ray densitometry data to show the density profile. The X-ray photographs of the thin samples were placed on top of the density profile, making it possible to observe the annual ring boundary (Fig. 2f). Once the annual rings were delimited and only four density profiles were detected, all of the rings from the density profiles were classified according to pattern. The classification was established by visually observing all density profiles. In this step, the variations in density across the ring, the peak density presence, the presence or lack of false annual rings, and the stability of density across the annual ring were observed. According to Jacquin et al. (2017), several different types of density

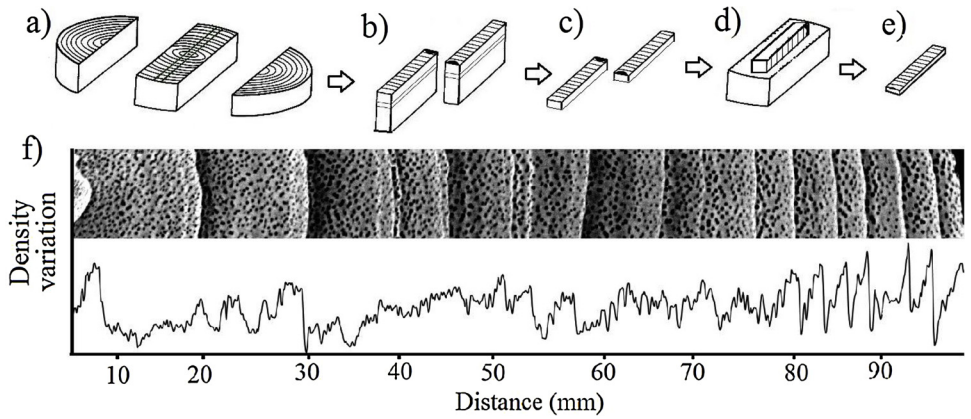


**Fig. 2.** Thin sample for X-ray exposure obtained from cross-sections sampled from a stem section of *Tectona grandis* trees (a–e) and density vs distance scatterplot from the pith with X-ray photographs, (f) density variation profile.

profiles can be found; however, the intra-ring wood density profile could not be applied to the annual rings of *T. grandis* trees from fast-growth plantations. Teak is a tropical species so its growth dynamics are different those of temperate species.

### 2.7. Sapwood and heartwood boundary in density profiles

Thin cross sections were sanded with 100, 200, 400, 800 and 1200 grit sandpaper. Afterwards, color photographs of each thin sample were obtained using a high-resolution scanner (Fig. 2f). The heartwood-sapwood boundary was then established using the photographs and density profiles. We therefore established whether the density profiles obtained from X-ray densitometry could be used to determine the end of the heartwood and the beginning of the sapwood. The color digital photograph of the heartwood-sapwood boundary was placed on the x–y graphic in the region of the density profile, close to the heartwood-sapwood boundary. Microscopic photographs were also used together with X-ray densitometry data to show the heartwood-sapwood boundary and the density variation. Using a microtome, a cross-section of the heartwood-sapwood boundary was prepared (American Optical Corp model 860); a macroscopic digital photographs were then taken using a stereoscope (Fisher Scientific).

### 2.8. Data analysis

The density values were graphed in relation to the annual ring widths and the density profiles were classified and counted by type of annual ring in a frequency table. The total percentages of each type of annual ring, as well as the percentages of each ring type at different tree ages, were obtained.

## 3. Results

### 3.1. Wood density profile between annual rings

The wood density profile pattern between annual rings showed that at early ages —trees between 0 and 8 years of age— it is not possible to determine annual ring boundaries using X-ray densitometry. The delimitation of growth rings by means of wood density profiles was confusing and any peak density was observed in these sections. Fig. 3 a–c shows the fuzzy delimitation of the annual rings for one sample, which is consistent with the results for every tree analyzed. When trees are between 8 and 12 years of age, annual ring boundaries become more evident in the X-ray densitometry profile: density values decrease after a slight increase at the ring's boundary. However, the ring boundary is not yet well defined. Fig. 3d-f shows a slight increase in wood density for one tree example, which is consistent with the results for every tree analyzed. At ages above 14 years (Fig. 3g-l), the boundary of each annual ring becomes better defined with increasing tree age, and a peak in density occurs at the ring's boundary, followed by an immediate decline. Fig. 3g-l shows well-defined annual rings for one tree example, which is consistent with the results for every tree analyzed.

Another important result was the observation that wood sample preparation with sandpaper for microscope observation helps to prevent unclear patterns in X-ray densitometry measurements. This is especially true for young trees, as sanding makes the rings easier to observe. The difference between the visibility of the annual ring boundary in the X-ray profile compared to its visibility under a microscope is greatest when the tree is young (< 8 years; Fig. 3a–c). As the tree ages, its ring boundaries becomes equally evident in the wood density profile and under a microscope (Fig. 3e-f).

### 3.2. Wood density profile within annual rings

Wood density profiles within annual rings (Fig. 4) were described according to the following four categories:

(1) uniform: the density variation remains constant within the annual ring, with no significant changes in the slope (Fig. 4a).
(2) stable growth: density is constant in a section of annual ring and begins to increase at the ring center until reaching the boundary of the ring (Fig. 4b). Alternatively, density increases continuously from the start of the ring until its end (Fig. 4c).
(3) unstable growth: a first growth phase can be observed, followed by a decrease. As a result, there may be 2–3 density peaks at the center of the annual ring (Fig. 4d).
(4) false: an early ring boundary with a density peak between 2 mm and 4 mm can be observed (Fig. 4e).

Classification of the 4 types of wood density profiles within annual rings relative to tree age showed that type 1 (uniform) profiles show an increase in the frequency of occurrence between ages 5 and 23, with 5–13% of total annual ring counted (Fig. 5a). However, profiles 2, 3, and 4 occur more frequently as the tree increases in age, with differences in the percentages for the three types of profiles (Fig. 5b).

An evaluation of the wood density profile within annual rings showed that the type 1 density profile occurred least often (6%; Fig. 5c). Density profiles types 2, 3, and 4 (growing, unstable, and false, respectively) occurred more frequently with increasing tree age, varying between 24% and 39%, with the lowest values at early ages and the highest values at ages between 23 and 25 years (Fig. 5a).

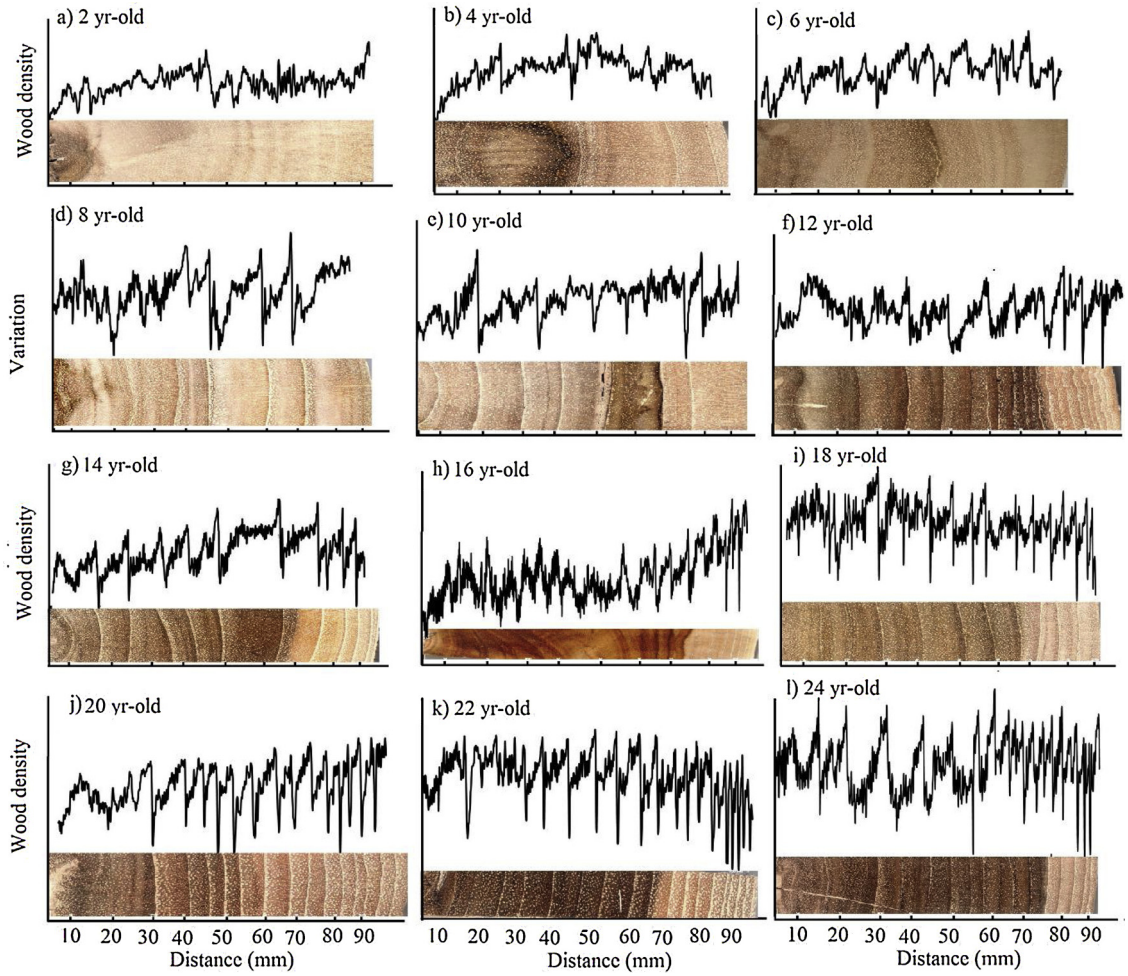


**Fig. 3.** Variation pattern of the rings observed in the X-ray densitometry at different ages in *Tectona grandis* trees in Costa Rica.

### 3.3. Wood density profile for sapwood-heartwood boundary

It is not always possible to determine the sapwood-heartwood boundary using the wood density profile. This is because the density variation in the sapwood-heartwood boundary can be influenced by the presence of annual rings. For example, this may occur when the sapwood-heartwood boundary is within the annual ring (Fig. 6a). In such cases, the wood density profile shows an increase in the density as far as the sapwood-heartwood boundary. Once the heartwood disappears, the density decreases in the sapwood section (Fig. 6a). A second case occurs when the sapwood-heartwood boundary coincides with the boundary between two annual rings (Fig. 8b). In this case, the wood density profile presents a decrease in density (Fig. 6b).

It was not possible to determine whether the sapwood-heartwood boundary in the annual ring boundary is related to the age or height of the tree because the visual limit between the sapwood-heartwood boundary is irregular in the cross section of the disc (Fig. 7). In irregular cross-sections, heartwood formation in the cross section is also irregular (Fig. 7a). In cases where the disc is circular, the sapwood-heartwood boundary may be regular in the cross section of the disc, but irregular at the boundary of the disc (Fig. 7b). In both cases, the sapwood-heartwood boundary may or may not be related to the annual ring.

## 4. Discussion

### 4.1. Wood density profile between annual rings

Wood density profiles for different tree ages showed that the annual ring boundary is diffuse and confusing for the first 8 years of a tree's life (Fig. 3a-d), when the annual ring boundary is not clearly visible (Fig. 3e-l). However, sample preparation makes annual ring identification easier (Fig. 3a-d). Therefore, microscopic analyses as shown in Fig. 3a-l should accompany the wood density profiles for annual ring identification in early-aged trees in fast-growth plantations. Teak tree growth rates at early ages explain the lack of clear annual rings for the first 8 years of a tree's life, particularly in fast-growth plantations where tree growth is accelerated in order to attain high wood production as quickly as possible (Kwame et al., 2014). Moreover, several authors (Bhat et al., 2001; Kumar et al., 2002; Bhat and Priya, 2004) maintain that at ages below 15 years, plantation trees present greater radial growth, resulting in wider annual rings with diffuse porosity (Sousa et al., 2012). This makes the annual ring boundary less visible by X-ray densitometry (Fig. 3a-d). In contrast, porosity is ring-porous and semi ring-porous at later ages; making ring boundaries more distinct (Fig. 3e-l).

Annual ring formation and the formation of annual ring boundaries were widely discussed by Nocetti et al. (2011). Annual ring formation under tropical conditions is influenced by climate, trunk eccentricity, tree competitiveness, and soil characteristics, all of which cause the development of annual rings to vary from one tree to another (Akachuku and Abolarin, 1989; Sousa et al., 2012). On plantations, silvicultural management activities are applied in the first 5–12 years of growth with the objective of maximizing tree diameter development (Bermejo et al., 2004). As a result, the wood density profiles of trees growing in tropical plantations are highly age-dependent (Fig. 3a-l).

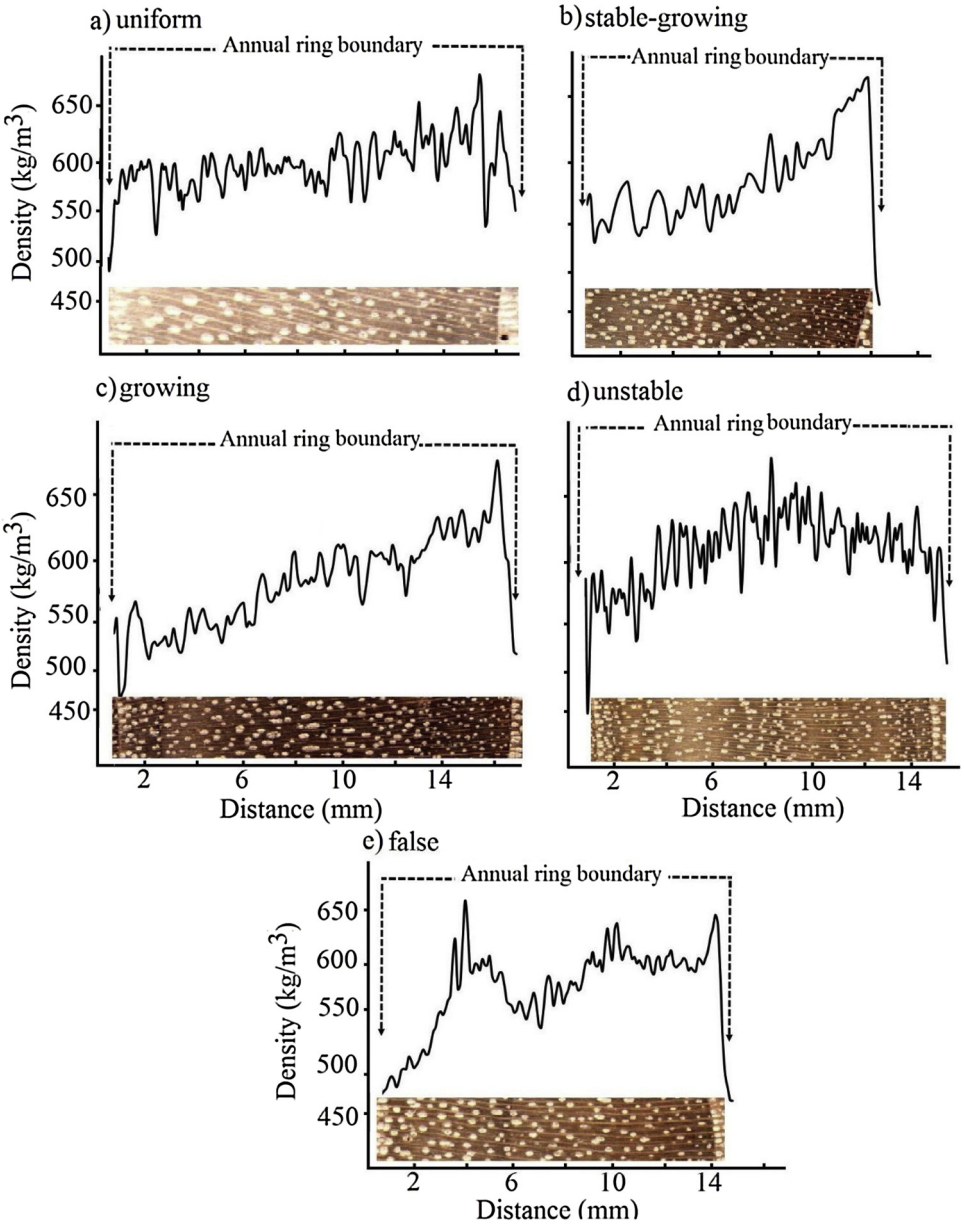


**Fig. 4.** Classification of the shape of the ring observed in the X-ray densitometry as (a) uniform, (b) stable-growing, (c) growing, (d) unstable and (e) false in *Tectona grandis* trees in Costa Rica.

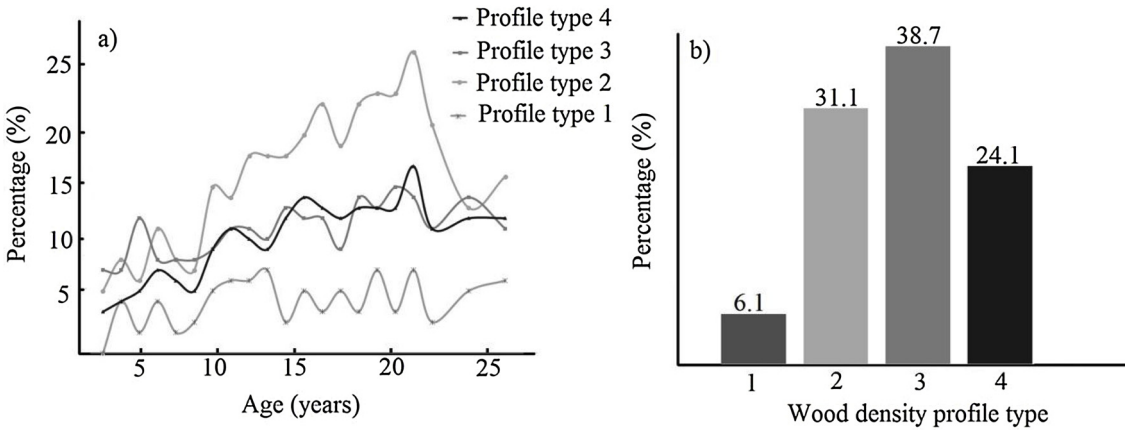


**Fig. 5.** Ring type frequency percentage according to wood density profile within annual rings at different ages: (a) profile type 1: uniform; (b) profile type 2: growing, profile type 3: unstable and profile type 4: false; and (c) total percentage per wood density profile type in *Tectona grandis* trees in Costa Rica.

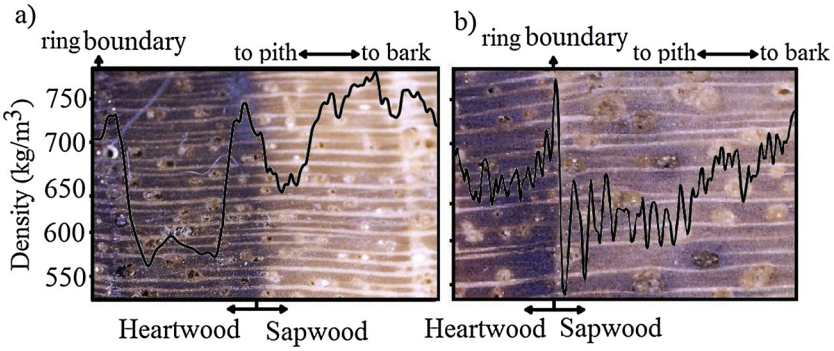


**Fig. 6.** Wood density variation throughout tree-rings and related anatomical wood cross-section, end of the latewood (a) in the middle of the ring and (b) in the annual ring boundary in *Tectona grandis* trees in Costa Rica.

### 4.2. Wood density profile within annual rings

In general, the early part of an annual ring is comprised of a narrow band of abundant and large lumen vessels, which is the reason why tree-ring density values are low at the beginning of an annual ring. The vessel lumen gradually decreases toward the end of the annual ring and the wood density gradually increases (Nocetti et al., 2011). This behavior can be seen in wood density profiles for annual rings obtained in the present study, specifically, in type 2 (stable growth) and 3 (unstable growth) annual rings (Fig. 4a–c). However, annual ring formation is sensitive to environmental changes, especially changes in temperature and water availability (Schweingruber, 2007; De Micco et al., 2016). Abrupt changes in the environment —as is common in tropical climates, where h precipitation/moisture is variables throughout the year— interrupt the continuity of cambial activity (De Micco et al., 2016). As a result, cambium cells, which define the diameter and frequency of the vessels at the beginning of the ring, vary. The diameter and frequency of these vessels therefore decrease at the end of the annual ring, thus increasing the wood density (Worbes, 2010). This behavior is evident in the annual rings of type 1, 2, and 3 (Fig. 4a–c).

However, under variable tropical climate conditions, multiple tree growth zones may appear during the same year. For example, fluctuations in precipitation during the rainy season may cause density variations within a single ring (Bhat and Priya, 2004; Dié et al., 2012). Such variations or anomalies during the rainy season produce types 4 and 5 rings (Fig. 4 d–e). However, the assumptions regarding the formation of the different annual ring types lack substantial evidence or in Bhat and Priya (2004) and Dié et al. (2012) studies. Their theories for annual ring formation analysis is developed from descriptive data analysis. It is therefore important that all types of annual rings present in trees from fast-growth plantations should be studied in relation to climate.

Annual ring types 1 and 2 occur relatively consistently in plantation teak trees of different ages (Fig. 5). This is probably because these types, type 1 in particular, are present early in the tree's life. Annual ring types 3, 4, and 5 (Fig. 5b-c) occur more frequently in adult trees in fast-growth plantations. Annual ring types 4 and 5 in plantations more frequently exhibit in adult plantation tree because such trees are more sensitive to variations that alter normal ring development (Fig. 5d–e). The hormonal mechanisms that control wood formation explain the irregularity in the wood density profile of type 4 and 5 rings (Aloni, 2007). Auxin is the main hormone controlling growth in juvenile wood; its availability decreases with age (Aloni, 1991). The decrease in auxin causes an increase in cytosine segregation, which affects the synthesis rate of other hormones (Aloni, 2004; Aloni et al., 2006) and results in more sensitive cambium tissue development in adult trees. Under some climatic conditions, larger or smaller vessels develop over short periods throughout the year (Aloni, 2001). This phenomenon was evident in this study, as adult trees presented less uniform annual rings (Fig. 5a–c).

The X-ray densitometry results of this study indicate that adult trees from fast-growth plantations present better-defined annual rings relative to juvenile trees. However, it may be difficult to identify annual rings (e.g., ring types 4 and 5) in older trees due to variations in tree growth. It is therefore advisable to complement wood density profiles

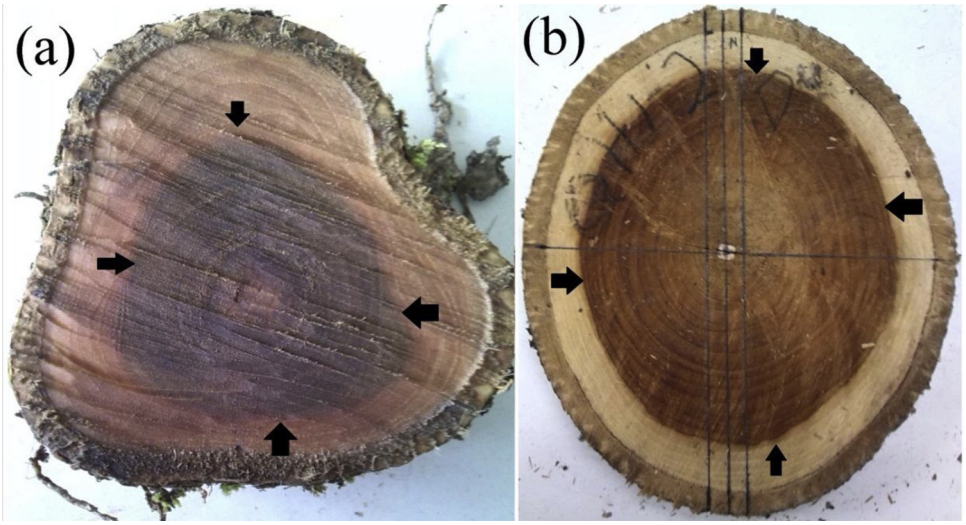


**Fig. 7.** Sapwood-heartwood boundary in cross-sections in *Tectona grandis* trees growing in fast-growth plantations. (a) Irregular boundary present in irregular cross-section and (b) relative regularity of sapwood-heartwood boundary. (Arrows indicate sapwood-heartwood boundary).

with well-sanded samples to help with the identification of annual rings.

### 4.3. Wood density profile for sapwood-heartwood boundary

The sapwood-heartwood boundary appears as a decrease in wood density, either within the ring (Fig. 6a) or at the ring boundary (Fig. 6b). The location of the boundary does not occur uniformly in the cross section of the tree (Fig. 7). The transition to heartwood formation is complex and depends on many growth factors (Wang and Stewart, 2012; Moya et al., 2014). Heartwood formation at different tree heights has not been widely studied in *T. grandis*, but it has been noted that the xylem produced by cambium at a specific height will be farther from the crown as the tree ages (Mvolo et al., 2015). Therefore, heartwood formation will not appear in the same way in a group of trees or even in an individual tree. Instead, it will depend on the maturation of the tree and the sampling height. As shown by the present study, although it is possible to utilize the wood density profile to determine the sapwood-heartwood boundary, the results are highly variable. Due to the irregularity of heartwood formation (Fig. 7a), the wood density profile and the cross section of the disc must be observed exhaustively.

## 5. Conclusion

Wood density profiles for *T. grandis* obtained via X-ray densitometry show a lack of annual ring definition during the first ~8 years of the tree's life. The poor definition of annual rings is due to high growth rates. As trees age, however, annual rings become more clearly defined and wood density profiles become more distinct. Four types of density profiles within annual rings were observed and classified: uniform (type 1), stable growth (type 2), unstable growth (type 3), and false (type 4). Wood density profile type 1 is common in trees under 8 years old and in more mature trees. As trees age, however, the within ring density profiles become better defined and wood density profiles type 2, 3, and 4 become more common. Although the wood density profiles of older trees show ring formation more clearly, it is advisable to sand samples to improve ring visibility.

The wood density profiles show the sapwood-heartwood boundary, but this boundary may be confused with a change in annual rings because the ring division may coincide with the sapwood-heartwood boundary. When the sapwood-heartwood boundary occurs within the annual ring, it is observed as an abrupt decrease in density. So, the cross section of the disc should be observed since the sapwood-heartwood boundary is irregular in the cross section of the tree.

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